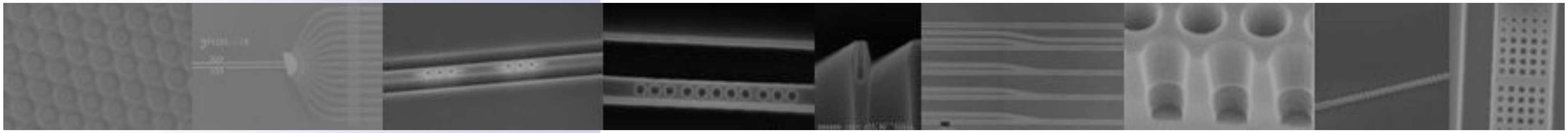


Electron-Beam Nanolithography

Emerging Technology Communications Institute

Learn how to write at the nanometer scale

Aju Jugessur Ph.D.

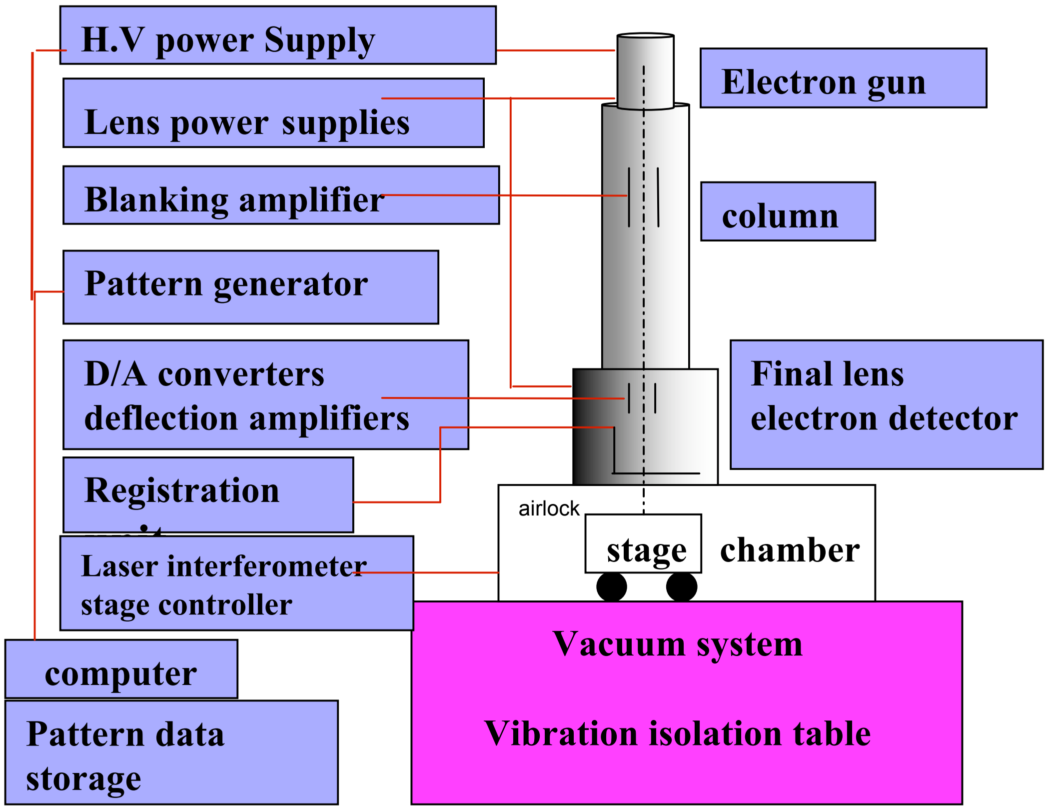
Training Modules Outline

- Introduction to E-Beam Lithography – 1hr
- Electron-Solid Interactions – 1hr
- E-Beam Lithography System EBPG5000+ - 2hrs
- Sample and Data Processing Protocols – 2 hrs
- Hands-on and Lab demonstration – 3 hrs

Introduction

- Electron Beam Lithography (EBL) –
  specialized technique for creating extremely fine patterns at the submicron or nanoscale, i.e 100 nm or smaller
- Basically, it consists of scanning a beam of electrons across a surface covered with a resist film sensitive to electrons
- First EBL machines based on SEMs developed in late 1960’s
- Followed by the discovery of PMMA (polymethyl methacrylate)

Block diagram of EBL tool



EBL column

- electron source
- lenses
- mechanism to deflect beam
- blanker - for turning beam on and off
- stigmator - for correcting any astigmatism
- apertures - to help define beam
- alignment systems – center beam
- electron detector – assist with focusing, locating marks

Applications of EBL technology

- Chrome-on-glass optical mask fabrication
  (for electronic integrated circuits)
- Direct write for advanced device prototyping
  (specialty products such as GaAs Integrated circuits and optical waveguides)
- High-frequency electronics devices –
  Gatelengths in the 100 nm range can be produced with good process latitude and yield
- Photonics and Optoelectronics devices –
  wavelength filters, Bragg gratings, optical waveguides and diffractive patterns
- Masters and molds for Nano-Imprint Lithography
- Biological and lab-on-a-chip applications
- Quantum computing device fabrication

Electron-optics

- Electron optics are a very close analog of light optics

  Most of the principles of an electron beam column can be understood by thinking of electrons as rays of light

- Electrons source emission – Thermionic (heating a metal), Field Emission (applying Electric field)
- Key parameters: virtual source size (µm), brightness (A/cm^2/sr), energy spread of electrons (eV)

Brightness can be compared to intensity in light optics – brighter the electron source, higher the current.

Beam with a wide energy spread (undesirable) is similar to white light

Beam with narrow energy spread comparable to monochromatic light

Electron-Optics….

Key element in micro/nanofabrication: ability to tightly focus particle beams

Particle energy E_0 (eV)

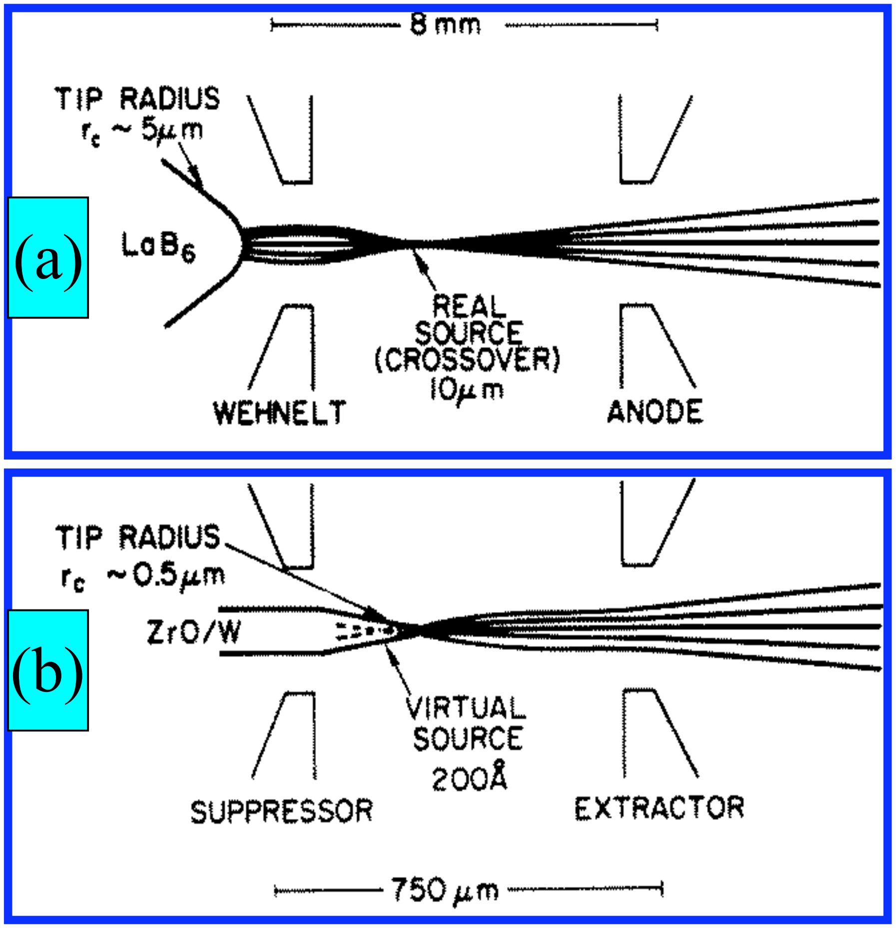
Particle	1	10	10^2	10^3	10^4	10^5	10^6
Photons $\lambda=1.2399/E_0$ µm	1.24	1.24×10^{-1}	1.24×10^{-2}	1.24×10^{-3}	1.24×10^{-4}	1.24×10^{-5}	1.24×10^{-6}
Electrons $1.23\times10^{-3}/(E_0 + 10^{-6}E_0^2)^{1/2}$	1.23×10^{-3}	3.88×10^{-3}	1.23×10^{-4}	3.88×10^{-5}	1.22×10^{-5}	3.70×10^{-6}	8.7×10^{-7}
Protons $\lambda = 28\times10^{-6}/E_0^{1/2}$ µm	2.87×10^{-5}	9.07×10^{-6}	2.87×10^{-6}	9.07×10^{-7}	2.87×10^{-7}	9.07×10^{-8}	2.87×10^{-8}

Particle Wavelengths (µm) at various particle energies E_0 (eV)

Electron source types

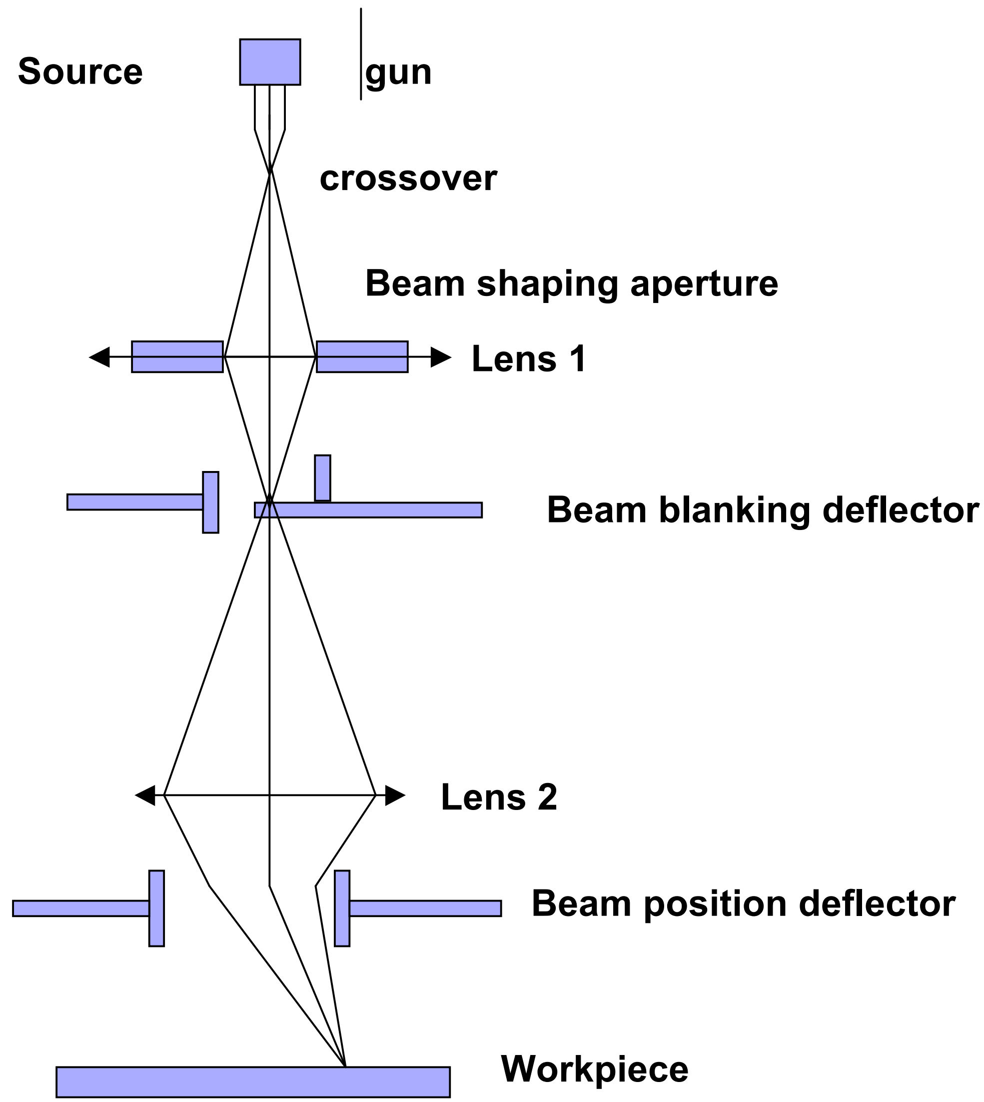
Source type	Brightness ($A/cm^2/sr$)	Source size	Energy Spread (eV)	Vacuum requirement (Torr)
Tungsten (thermionic)	$\sim 10^5$	25 µm	2-3	10^{-6}
LaB_6 (thermionic)	$\sim 10^6$	10 µm	2-3	10^{-8}
Thermal (Schottky) Field emitter	$\sim 10^8$	20 nm	0.9	10^{-9}
Cold field emitter	$\sim 10^9$	5 nm	0.22	10^{-10}

Electron source



- **Lenses** – both electro-static and electro-magnetic to converge main beam into smaller spot
- **Beam Blanker** – switches beam on and off as required
- **Electron Optics** – beam formation and position control
- **Vacuum System** – maintain different vacuum levels
- **Pattern Generator**- transfers pattern data to beam for exposure
- **Stage System** – moves substrate for large area exposure
- **Control Electronics** – operator interface, hardware and software controls
- **Correction Systems** – measure and compensate system distortions

Ray diagram of an electron optical system



More on Electron-optics components

- Quality of electron lenses are not as good as optical lenses – aberration problems.

  Spherical aberrations – outer zones of the lens focus more that inner zones

  Chromatic aberrations – electrons of slightly different energies get focused at different image planes.

  Can be reduced by reducing convergence angle of the system so that electrons confined to center of lenses – reduce current

  Electrostatic lenses have worse aberrations that magnetic lenses

- Beam blanker – (i) when beam is blanked, attenuation must be great, typically a value of 10^6 is specified

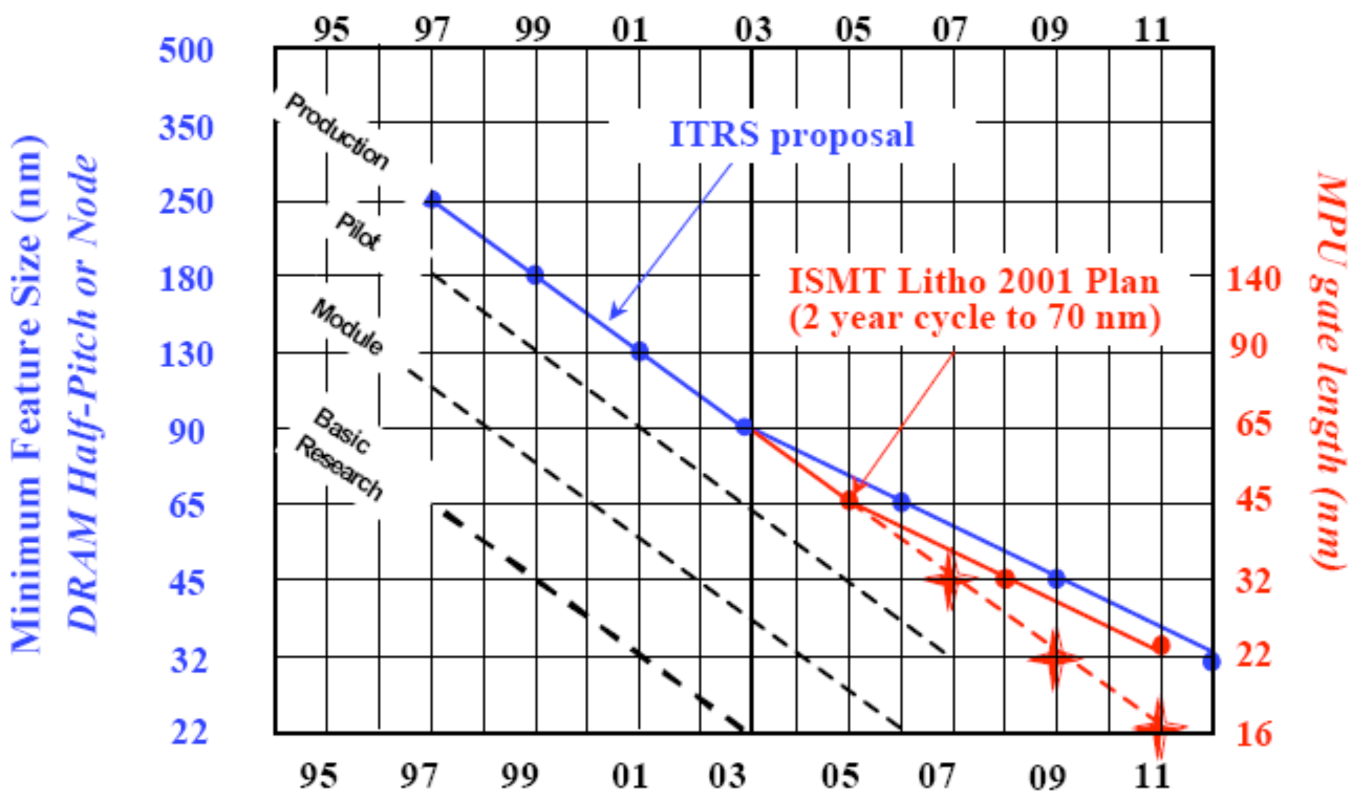
  (ii) any spurious beam motion introduced must be much smaller that size of a pattern pixel, typically < 0.1 μm of motion

  (iii) response time of blanker << pixel exposure time, typically response time << 100 ns

Future of E-Beam Lithography

ITRS Roadmap (Moore's law)

International Technology Roadmap for Semiconductors



Alternative Nanolithography techniques Contenders for NGL

- **Optical Lithography @ 157 nm**
- **EUV lithography @ 13.5 nm**
- **Ion Projection Lithography (IPL)**
- **Electron Projection Lithography (EPL)**
- **X ray lithography @ 1 nm**
- **Direct Write E-Beam Lithography**

What are NGL challenges

Technical Challenges

- **Resolution**
- **Throughput (80-120 W/H)**
- **CD control (10 % of nominal CD)**
- **Overlay (30 % of the node)**
- **Resist issues**

Economic challenges

- **Mask cost and fabrication delay**
- **Equipment cost**
- **Equipment ‘in time to market”**

Lithographic requirements

Year of Production Technology Node	2001 130nm	2003 90nm	2005 65nm	2007 45nm	2010 32nm	2013 22nm
Half-pitch (nm)	130	90	65	45	32	22
Contacts (nm)	150	100	70	50	35	25
Overlay (nm, mean + 3 sigma)	45	31	23	18	13	9
Gate length (nm, in resist)	90	53	35	25	18	13
Gate length (nm, post-etch)	65	37	25	18	13	9
Gate CD control (nm, 3 sigma, post-etch)	5.3	3.0	2.0	1.5	1.1	0.7

Limits of Optical Lithography

Resolution: $R = k_1 \lambda/NA$

Depth of Focus: $DOF = k_2 \lambda/NA^2$

To decrease R: λ need to decrease and increase NA

BUT, DOF decreases too

Need to decrease k_1

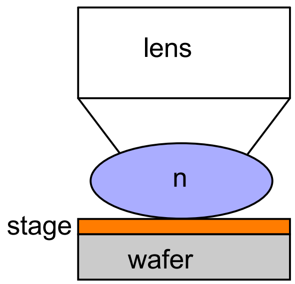
k_1 , optical engineering = function (resist, mask, illumination)

157 nm lithography

157 nm wavelength looked the natural and easiest path to be the next litho. After 193 nm but:

- **Problems to produce CaF_2 crystal in large amount**
- **Std. reticles and pellicles not transmitting**
- **New resist platform needed – under development**
- **2 yrs delay, 157 nm ‘not in time’**

Immersion lithography



$NA = n\sin\theta$, θ acceptance angle

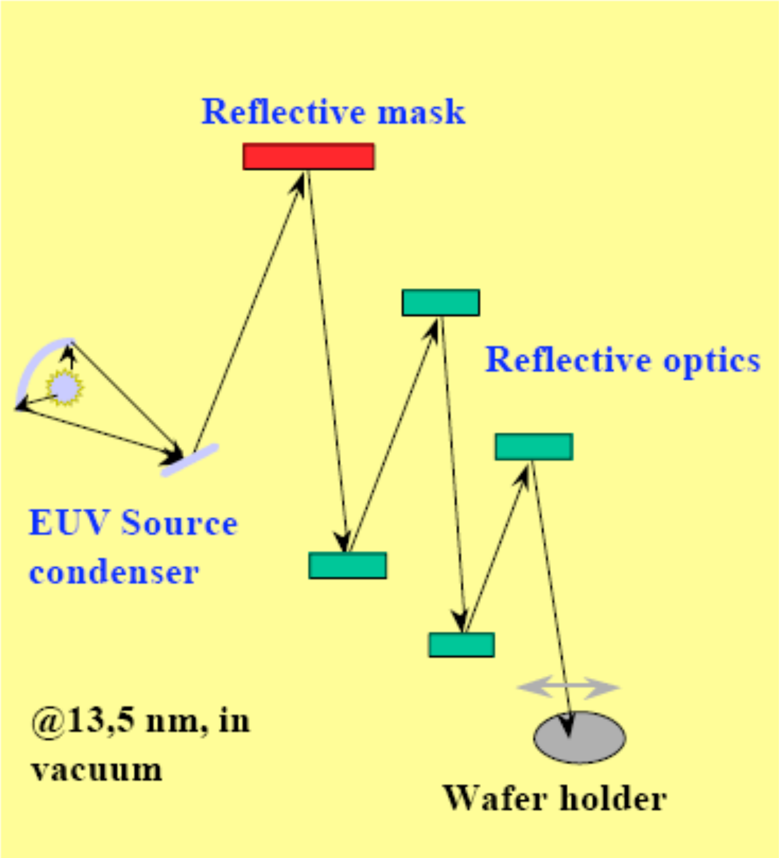
$R = k_1\lambda/NA$

$DOF = k_2/NA^2$

$R = k_1(\lambda/n)/\sin\theta$

	Medium	n	λ/n
193 nm dry	air	1.0	193 nm
193 nm immersion	H_2O	1.47	131 nm
157 nm dry	N_2	1.0	157 nm
157 nm immersion	PFPE	1.37 nm	115 nm

EUV lithography



Everything absorb EUV light

- Vacuum
- Reflective masks and optics

Sources: based on plasma (Xe,Sn,In) emitting in EUV (13.5 nm)

- Laser Produce Plasma (LPP)
- Discharge Produce Plasma (DPP)

Specifications very tight

- ML mirrors: 70% reflectivity
- Masks: defects < 10^{-3} defects/cm2
- optics: < 0.1 nm roughness
- sources: 120 W, no debris

Economics: masks costs tomorrow

NGL costs and availability

- $100-350 k/mask (1st year production), 3-5 months manufacturing cycle times
- $50-100 k/mask (3rd year in production) and 1-2 months manufacturing cycle times
- Introduction of cost-effective solutions

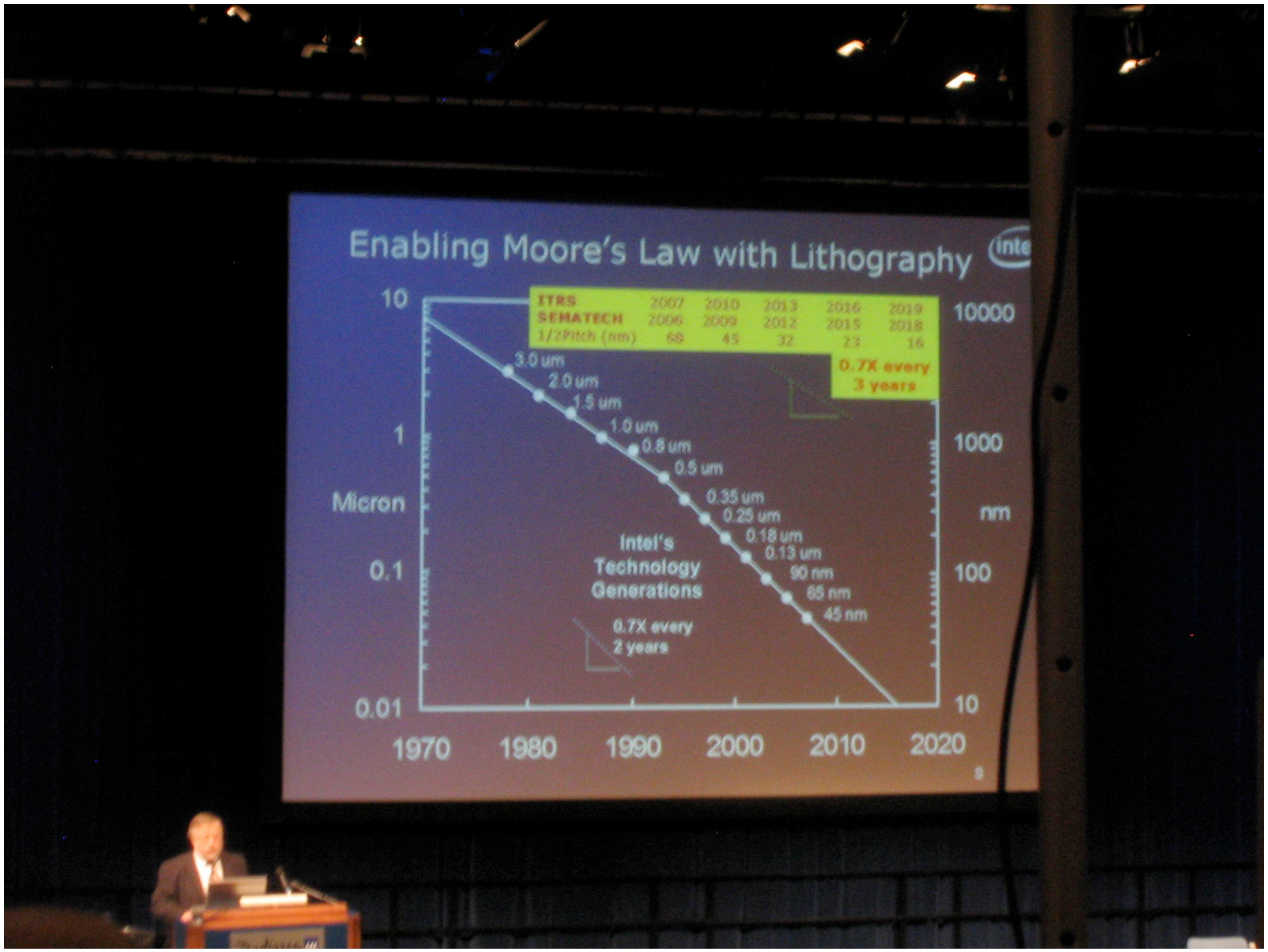
  * Mask-less Lithography; Shaped Beam/Multi-Column/ Multi-Beams

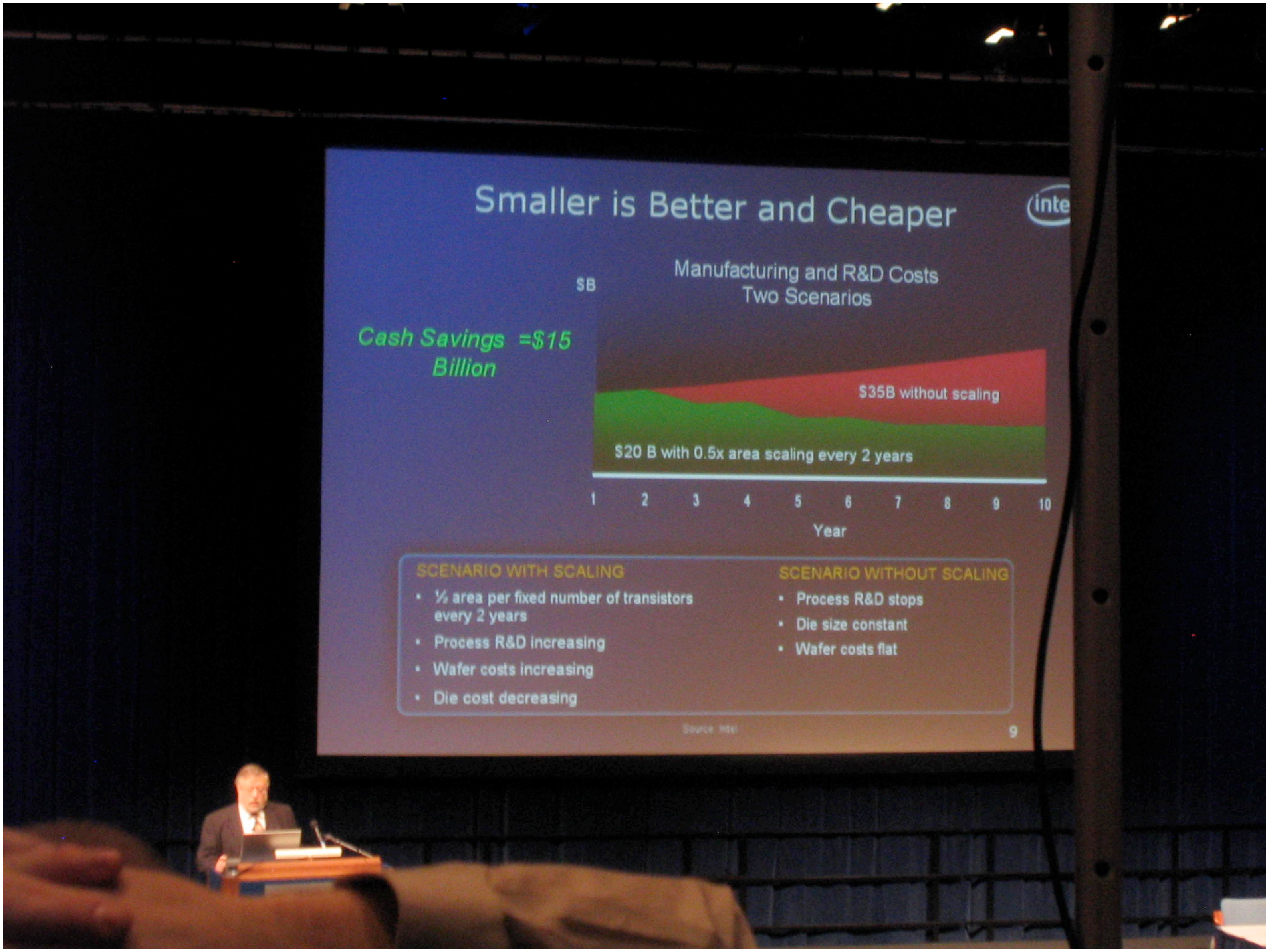
  * Electron Projection Lithography (EPL)

  * Nanoimprint lithography

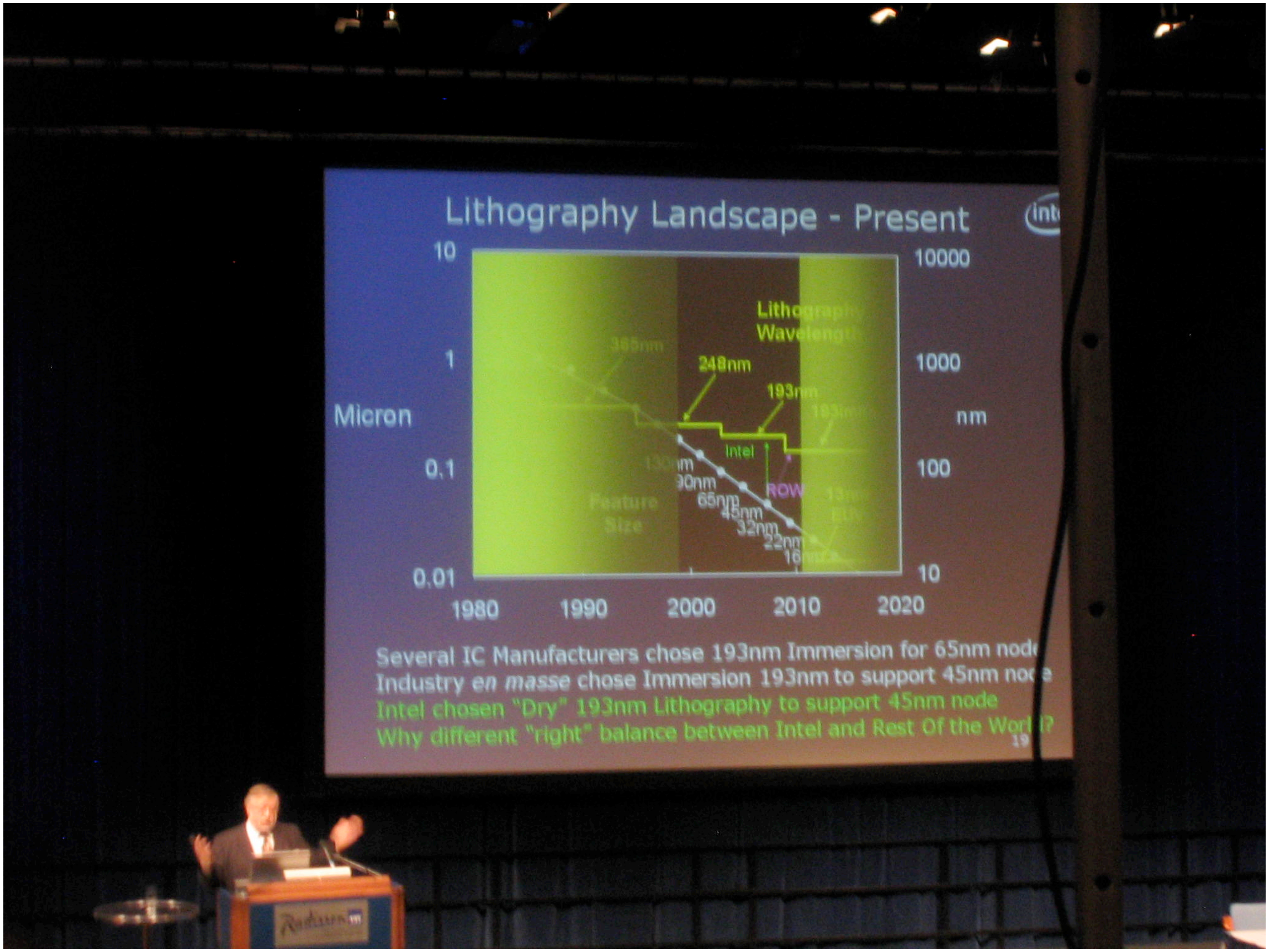
E-Beam Lithography prospects

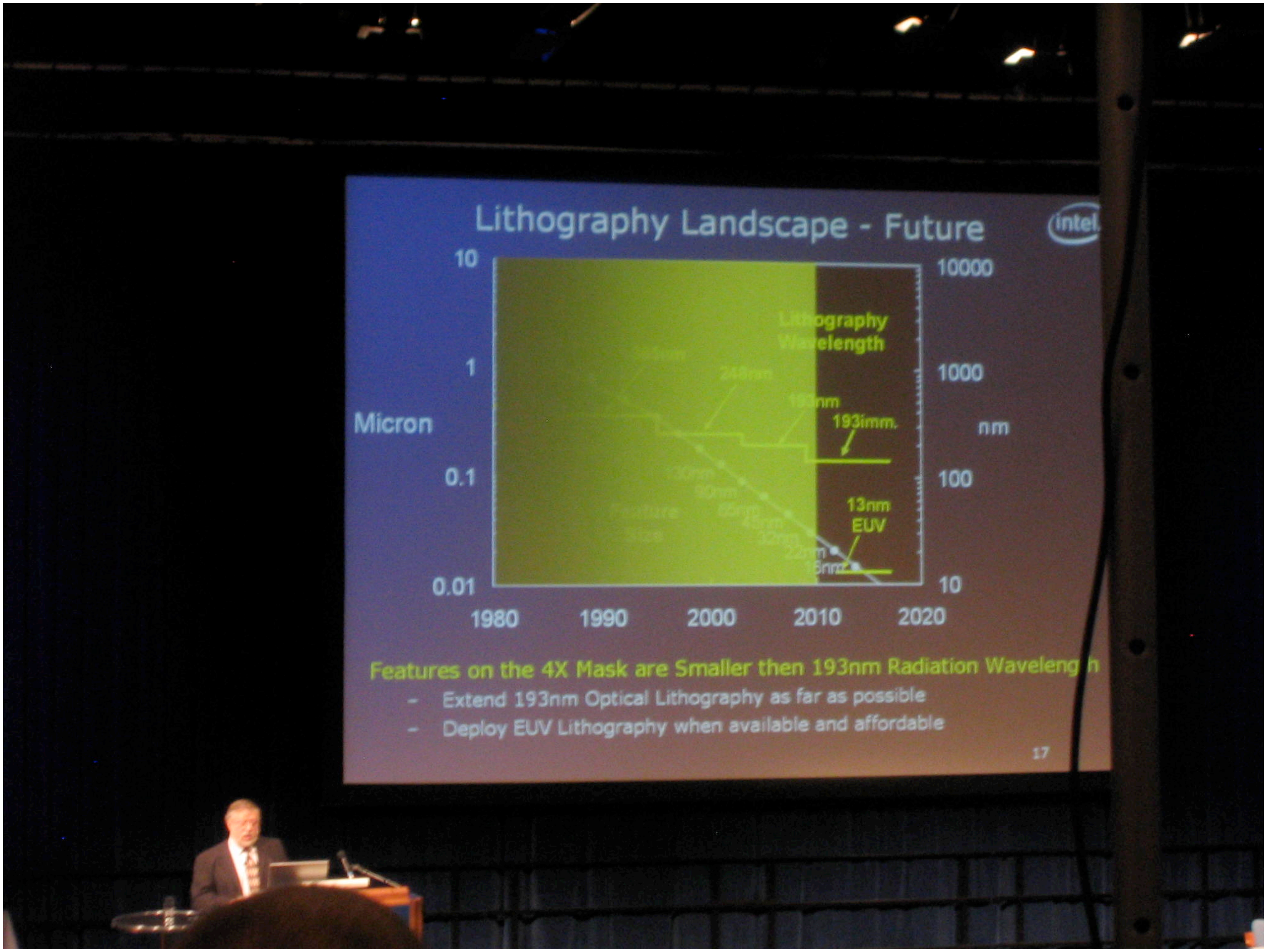
Yan Borodovsky, Intel Corporation – DUV still going strong but….
MNE 2007



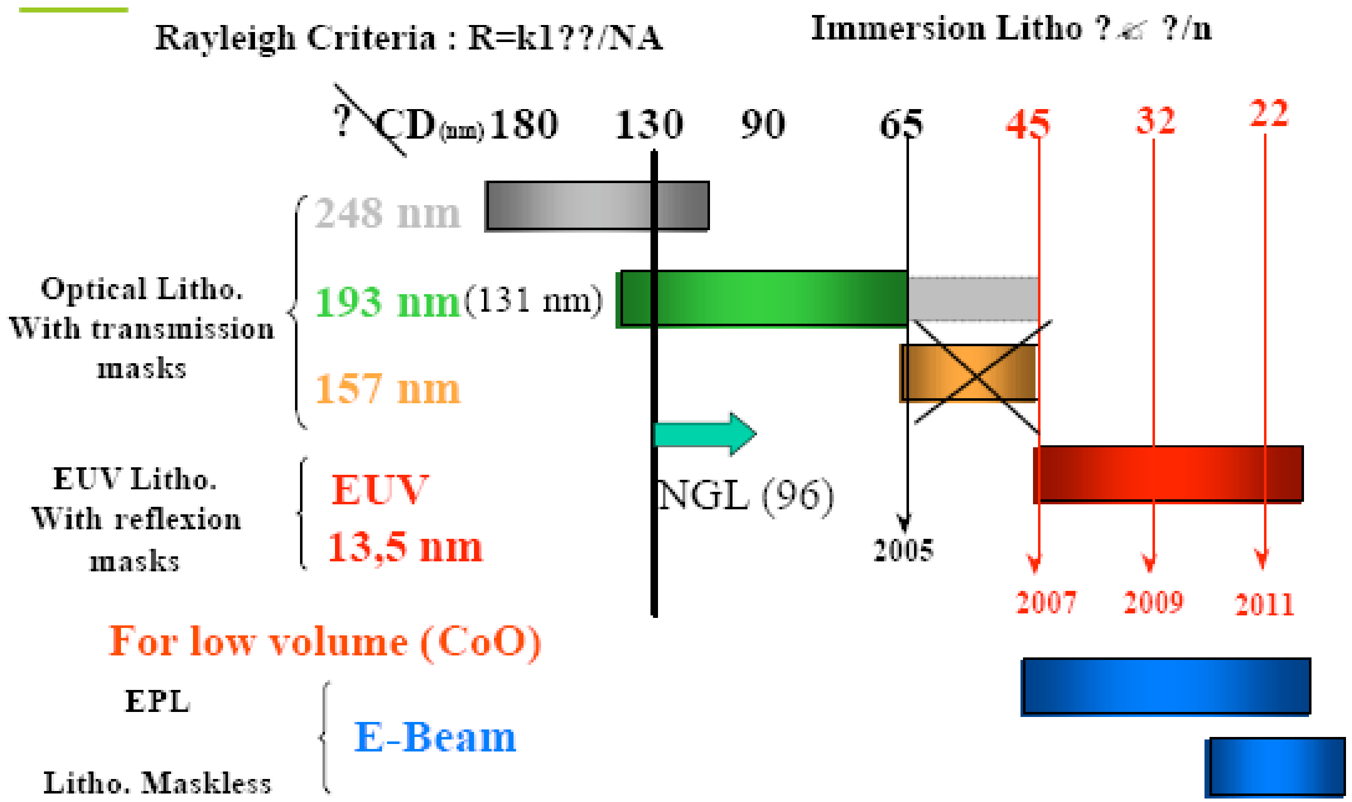


Smaller is Better and Cheaper
Manufacturing and R&D Costs
Two Scenarios
$B
Cash Savings =$15 Billion
$35B without scaling
$20 B with 0.5x area scaling every 2 years
1 2 3 4 5 6 7 8 9 10
Year
SCENARIO WITH SCALING
• ½ area per fixed number of transistors every 2 years
• Process R&D increasing
• Wafer costs increasing
• Die cost decreasing
SCENARIO WITHOUT SCALING
• Process R&D stops
• Die size constant
• Wafer costs flat
9


Lithography Landscape - Present
10
1
0.1
0.01
Micron
10000
1000
100
10
nm
248nm
193nm
Intel
ROW
90nm
65nm
45nm
32nm
22nm
Feature
Size
1980
1990
2000
2010
2020
Several IC Manufacturers chose 193nm Immersion for 65nm node
Industry *en masse* chose Immersion 193nm to support 45nm node
Intel chosen "Dry" 193nm Lithography to support 45nm node
Why different "right" balance between Intel and Rest Of the World?


Lithography Landscape - Future
intel
10
1
0.1
0.01
Micron
10000
1000
100
10
nm
Lithography
Wavelength
193nm
193imm.
13nm
EUV
1980
1990
2000
2010
2020
Features on the 4X Mask are Smaller then 193nm Radiation
- Extend 193nm Optical Lithography as far as possible
- Deploy EUV Lithography when available and affordable
17

Today's Strategy



Electron-Solid Interactions

Electron-Solid Interactions

- Electron beam is capable of forming extremely fine probes, however:

  * more complex mechanisms result when beam hits the work piece
- As electrons penetrate the resist, they experience many small angle scattering events - **forward scattering** - beam broadening
- As the electrons penetrate deeper through the resist and into the substrate, they undergo large angle scattering events, **backward scattering** – proximity effects
- Result of the above two processes – formation of secondary electrons

Forward Scattering

- The forward scattering effect during which the beam expands is given by

$$d_f = 0.9\left(R_t / V_b\right)^{1.5}$$

d_f is the effective increase in beam diameter in nanometers
R_t is the resist thickness in nanometers and
V_b is the beam voltage in kilovolts

For example: a resist thickness of 400 nm exposed at 100 kV will have d_f = 7 nm

Using thinner resist and higher accelerating voltage, d_f can be reduced

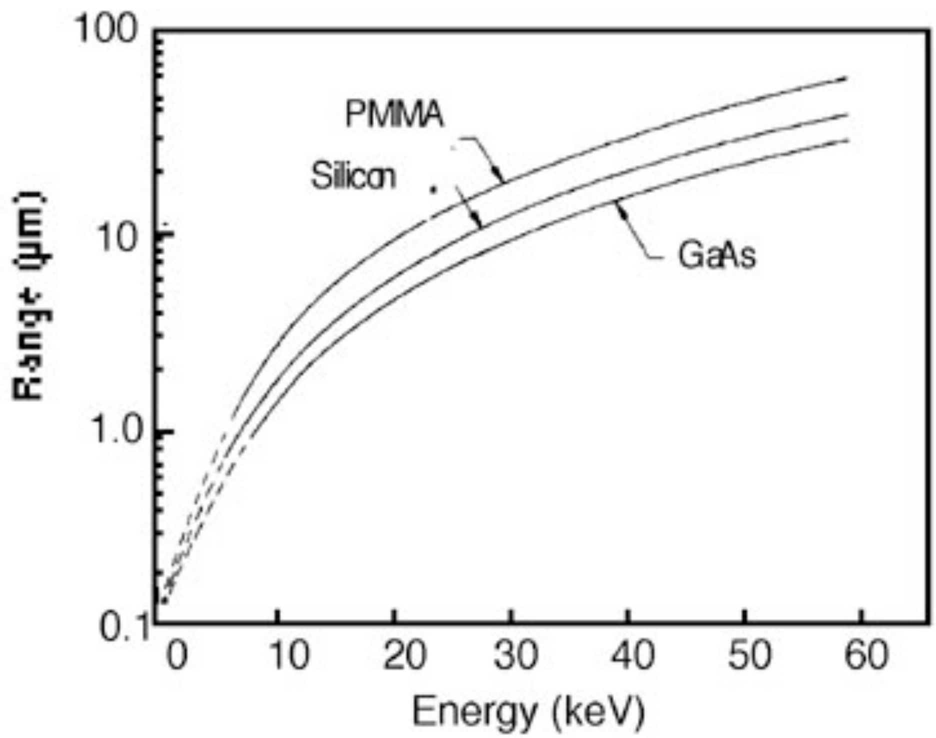
Backward Scattering

- As electrons penetrate the resist into the substrate, they experience large angle scattering events
- The electrons may return through the resist causing additional exposure – **proximity effects**
- Fraction of backscattered electrons (η) is roughly independent of beam energy
- Depends on substrate material – low atomic number gives less backscatter
- Range of backscattered electrons is longer at higher voltages
- Typical η values range from 0.17 for Silicon to 0.5 for tungsten or gold

Secondary electrons

- As primary electrons slow down, much of their energy is dissipated in the form of secondary electrons
- Their range is only a few nanometers – little contribution in proximity
- Energy distribution is between 2 to 50eV
- Net result is effective beam widening –largely accounts for the minimum practical resolution achieved
- Small fraction of secondary electrons may have significant energies - ~ 1keV – might contribute to proximity effects in the few tenths um range

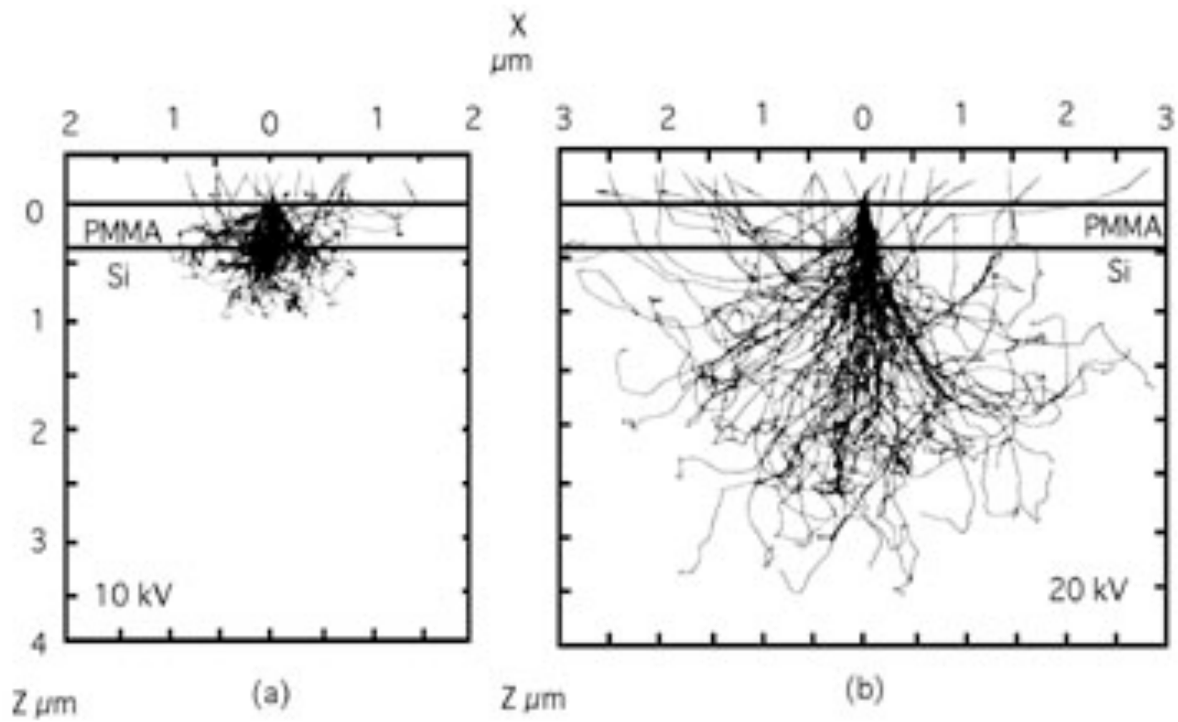
Electron range as a function of beam energy



Monte Carlo modeling

- Electron scattering in resists and substrates can be modeled with reasonable accuracy
- Input to the program contains parameters as electron energy, beam diameter, film thicknesses and densities
- Output is a plot of energy deposited in resist as a function of distance from center of beam
- Software for Monte Carlo simulation of electron irradiation is available from several sources

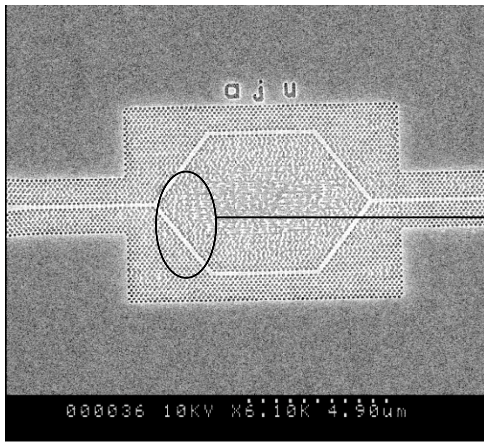
Monte Carlo simulations

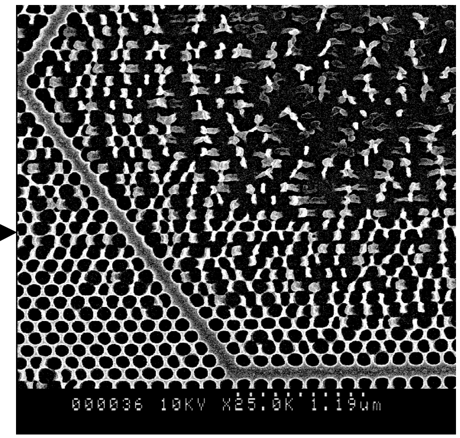


Source: D. F. Kyser and N. S. Viswanathan, “Monte Carlo simulation of spatially distributed beams in electron-beam lithography,” J. Vac. Sci. Technol. **12**(6), 1305-1308 (1975)

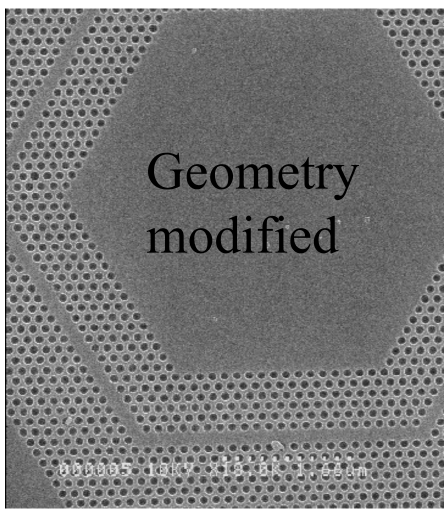
Proximity Effects

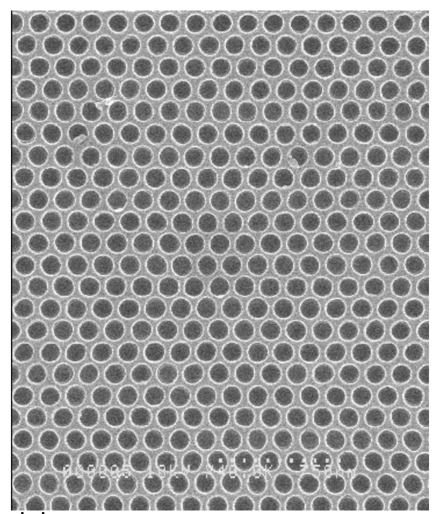
- Net result of electron scattering – dose delivered by electron beam tool is not confined to shapes that tool writes
- Resulting in linewidth/size variations





Proximity correction



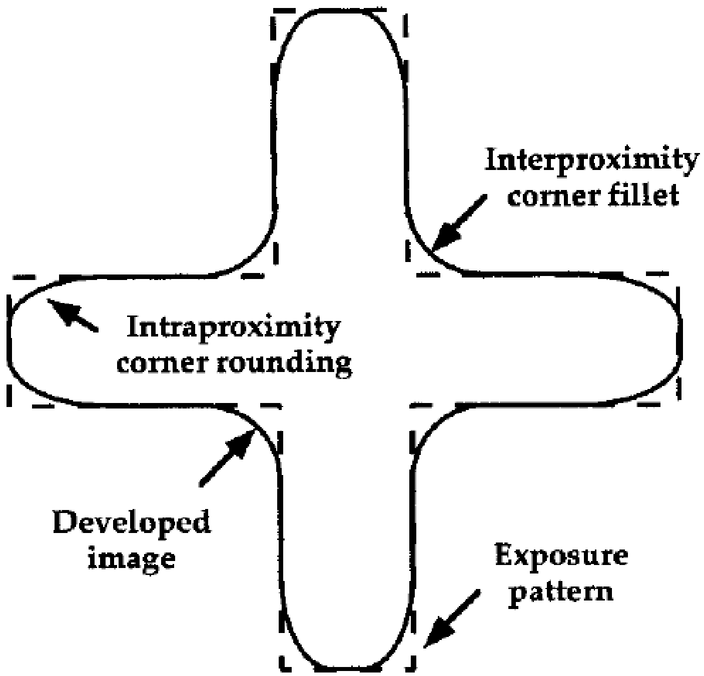


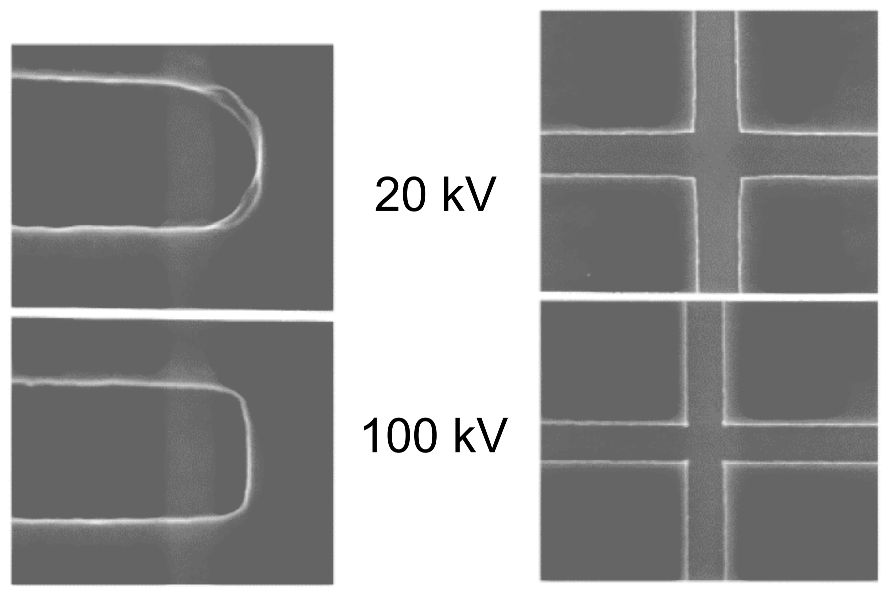
Dense areas:

dose modulation

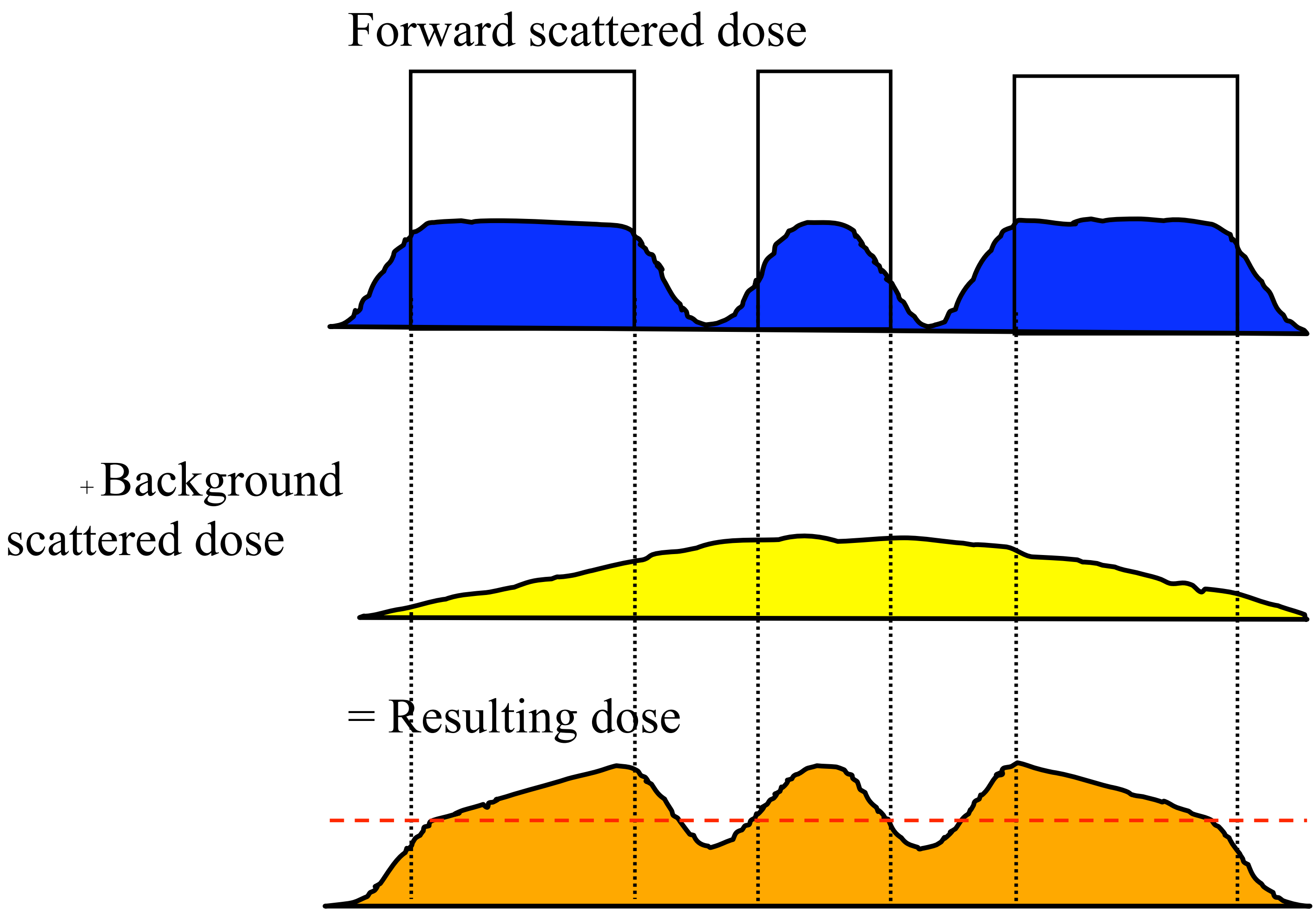
350 nm

Proximity effects





Proximity



Schematic illustration of proximity effects in electron beam lithography

Proximity Correction Methods

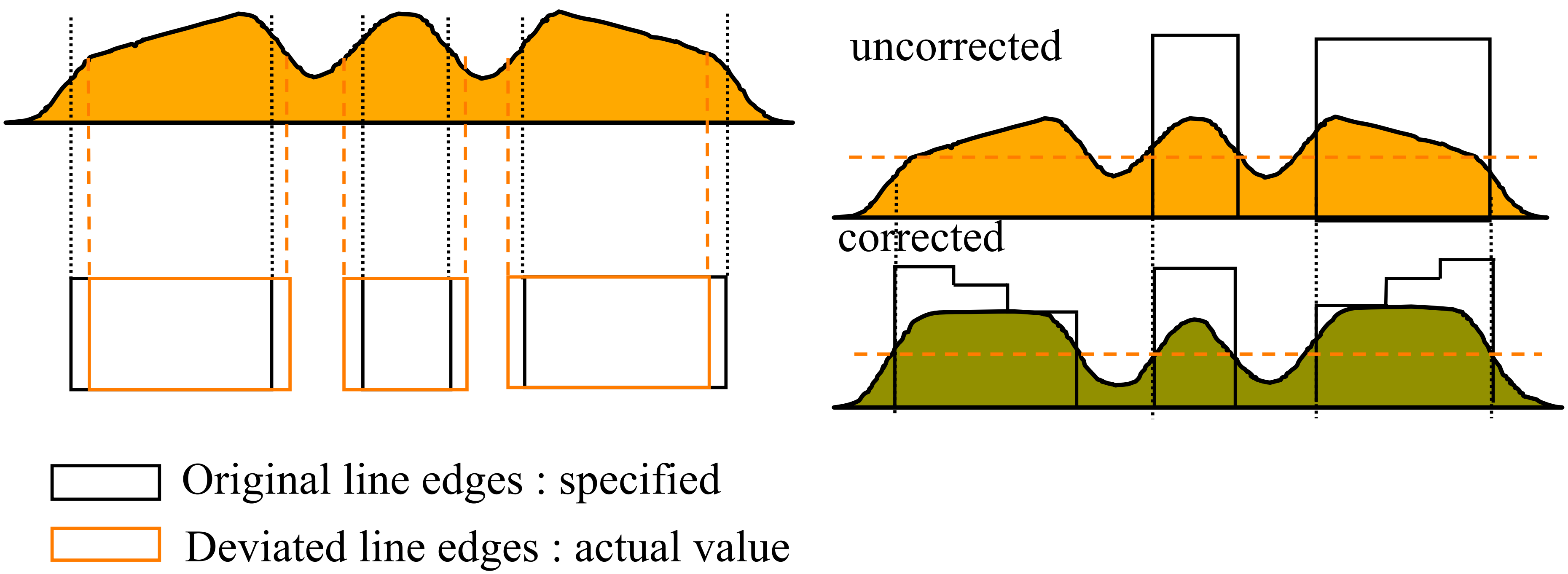
- Dose Modulation
- Pattern biasing
- Ghost technique
- Software packages: Proxeco, LayoutBeamer (~ >$100,000)

Patterns with uniform density and linewidth - proximity effects can be reduced simply by adjusting the overall dose until the desired size is reached

Dose modulation

- An algorithm where each individual shape in a pattern is assigned a specific dose and calculations of the shape to shape interactions are carried out computationally

Proximity effects on line edges



Proximity correction model

The model describing the normalised proximity function as the sum of two Gaussian functions is expressed as:

$$f(r) = \frac{1}{\pi(1+\gamma)}\left(\frac{1}{\alpha^2}\exp\left(\frac{-r^2}{\alpha^2}\right) + \frac{\gamma}{\xi}\exp\left(\frac{-r^2}{\xi^2}\right)\right)$$

where α is the width of direct exposure (forward scattering)

ξ is the width of back scattering

γ is the ratio ξ/α

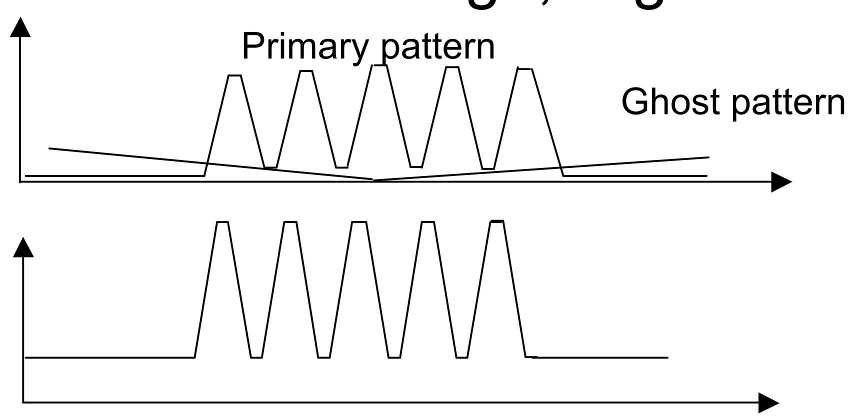
r is the distance from the centre of the Gaussian profile of the electron beam

Pattern biasing

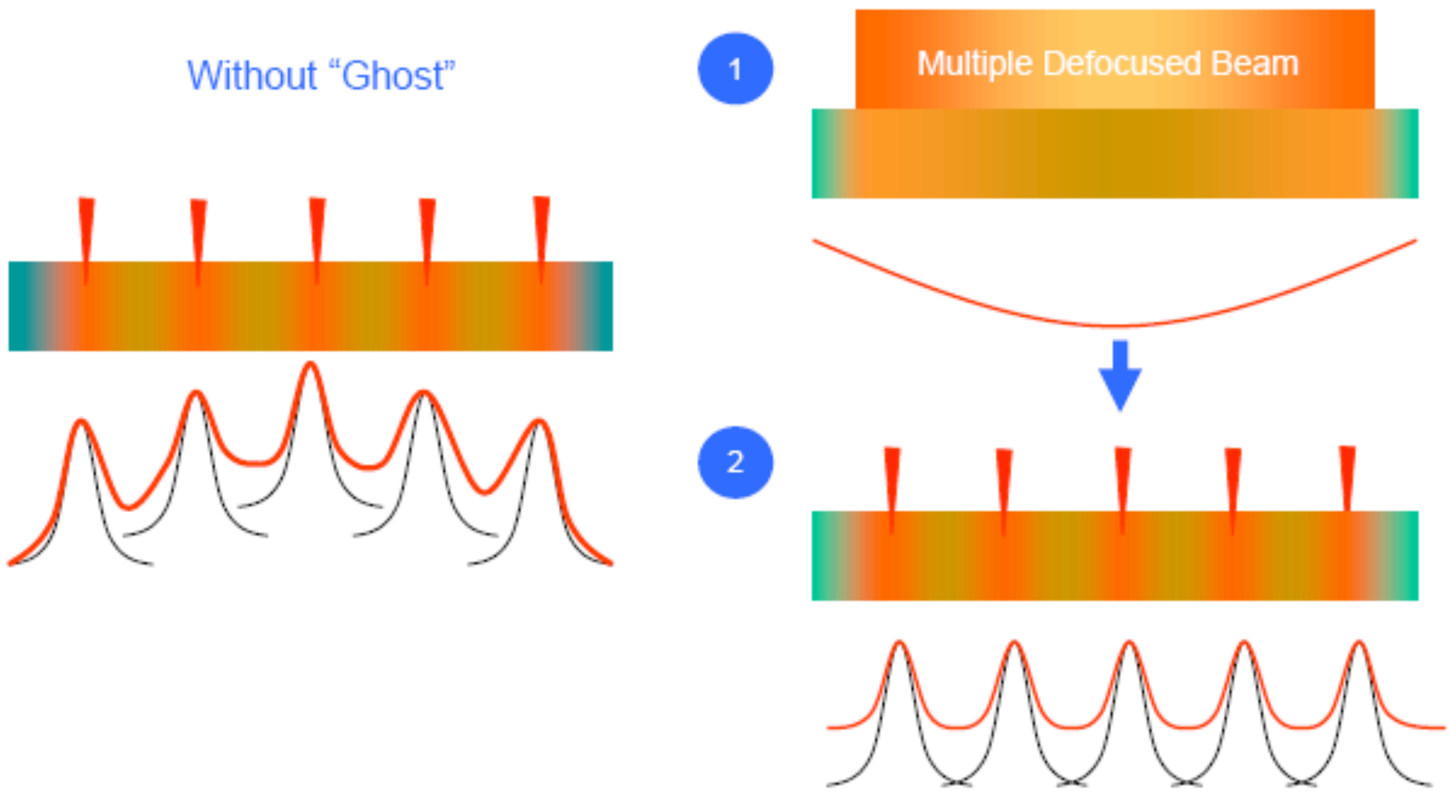
- Computationally similar approach to dose modulation – extra dose that dense patterns receive is compensated for by slightly reducing their size.
- Disadvantage: no dynamic range that dose modulation has; patterns containing both isolated and dense features will have reduced process lattitude.
- Pattern biasing can not be applied to features with dimensions close to pixel spacing

Ghost technique

- Does not require computation at all – inverse tone of pattern written with defocused beam to mimic the shape of the backscatter distribution.
- Dose of ghost pattern is also set to match the large area backscatter dose. After the defocused inverse image is written, the pattern will have a roughly uniform dose.
- Disadvantages: Extra data preparation and writing time; slight to moderate loss of contrast in resist image; slight loss in minimum resolution



Proximity Correction – “Ghost” Exposure



Proximity effects remarks

- E-Beam proximity effect can be reduced at high kV ~ 100 kV
- High acceleration voltage – more energy - range of backscattered electrons longer
- Fraction of back-scattered electrons is dependent on substrate material used – lower atomic number of material, lower the back scattering
- Secondary electrons have little contribution to proximity effect since range only few nanometers – responsible for bulk resist exposure
- Higher contrast resists can help minimize linewidth variations

Simple ways to reduce proximity effects

- Adjust acceleration voltage
- Split pattern into several writings using different doses
- Adjust pattern size and shape
- Adjust dose level to compensate scattering